BELLCOMM, INC.
1100 Seventeenth Street, N.W. Washington, D.C. 20036

SUBJECT: Comparisons of Circular and Elliptic Orbit Rendezvous for Manned Planetary Flyby Missions - Case 233

DATE: June 8, 1967

FROM: H. S. London

ABSTRACT

The injected weight capability for manned flyby missions using elliptic earth orbit rendezvous and S-IVC injection stages is estimated for uprated Saturn V's which have a capacity of 340,000 lbs. to a 100 nautical mile circular orbit. It is found that a spacecraft of between 175,000 and 210,000 lbs. gross weight, depending on whether two-stage or three-stage launch vehicles are used, can be injected on the 1977 triple-planet flyby with a total of three launches. This result is based on the use of S-IVC with standard propellant capacity. If restricted to circular orbit rendezvous, the gross spacecraft weight cannot exceed about 165,000 lbs. even if the S-IVC propellant capacity is stretched to about 280,000 lbs. (with standard S-IVC propellant capacity the payload would be only about 130,000 lbs.). With a fourth launch and circular orbit rendezvous, the payload would be 196,000 - 240,000 lbs. depending on S-IVC propellant capacity.

Similar calculations have been carried out for standard (non-uprated) Saturn V's by Douglas Aircraft. Their results also indicate substantial gains through the use of elliptic orbit rendezvous e.g., 40,000 lbs. greater payload for the same number of launches. By combining suborbital start of the S-IVC with elliptic orbit rendezvous, four launches of non-uprated Saturn V's permit injection of a 200,000 lb. spacecraft on the 1977 triple-planet flyby.

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MEMORANDUM FOR FILE

Introduction

Elliptic orbit rendezvous allows the use of each launch vehicle to its maximum performance capability, rather than arbitrarily cutting it off and staging in a low altitude circular orbit. Two-stage Saturn V's can place a gross payload of about 275,000 lbs. (greater for uprated versions) in a 100 nautical mile orbit, e.g.; if the spacecraft weight is less than this, then some of the performance capability of that launch vehicle goes to waste as long as rendezvous and assembly operations take place in low circular orbit. Similarly, a fully loaded (unstretched) S-IVC weighs about 287,000 lbs., including aft interstage and IU, so that uprated Saturn V's with greater payload-to-low-orbit capability would not be fully utilized if they were used to place S-IVC's in low circular orbit.

Substantially improved overall performance can be attained if the spacecraft is placed in the highest energy elliptic orbit within the launch vehicle capability for that weight, and rendezvousing with the S-IVC injection stages in that orbit. The relative improvement associated with elliptic orbit rendezvous depends upon the mission velocity requirement, launch vehicle capability, and number of launches. Specific examples are given in this memorandum.

Uprated Saturn V - 340 K to Low Orbit

As one example, an uprated Saturn V with the following features was selected:

Stretched S-IC stage

F-1 engines uprated to 1.8×10^6 pounds thrust

Uprated J-2S - 434 sec. Isp @ 235,000 lbs. thrust.

This vehicle is estimated to have a capability of about 340,000 pounds (everything above the S-II stage) to a 100 nautical mile circular orbit in the two-stage version, or about 127,000 lbs. to trans-lunar injection (above the IU) in the three-stage version. With these as reference figures, payload-velocity curves were estimated for the two and three-stage versions by

[redacted]

calculating the variation of ideal ΔV with payload weight. These curves, shown in Figure 1, do not account for the variation in gravity losses with payload weight. The payload shown for the two-stage version includes everything above the S-II stage, i.e., IU, aft interstage on the S-IVC, etc. are included as part of this payload. The three-stage payload includes everything above the IU. Also shown in Figure 1 are the orbit period and apogee altitude associated with a given payload and velocity.

A weight breakdown for the S-IVC is given below. This is based on a weight statement given by MSFC at the March, 1967 JAG meeting, with two exceptions: (1) it is assumed here that all IU's are jettisoned before leaving earth orbit, (2) the S-IVC is fully loaded, with about 213,500 lbs. of main-burn propellant and an additional 16,500 lbs. of propellant allowed for idle-mode, boiloff, transients, and residuals.

S-IVC Weight Breakdown

Main-Burn Propellants	213,500	
Stage Dry Weight	33,400	(Includes Forward APS Modules)
Residuals	2,500	
Jettison Before S-IVC First Burn (Aft Interstage and Nose Fairing)	10,400	
Jettison Before OLV Assembly (IU; Aft APS Modules and APS Propellant; Transients, Idle Mode, and Boiloff Propellants)	26,700	
TOTAL	286,500	

It was assumed that for circular orbit rendezvous, 4,100 lbs. of the main-burn propellant is used for circularization in a 263.5 nautical mile circular orbit, so that 209,400 lbs. remains for the out-of-orbit injection.

Mission Profile

It is assumed that in elliptic orbit rendezvous the spacecraft is injected into the maximum eccentricity orbit (with perigee altitude of 100 nautical miles) which the launch vehicle is capable of. Each S-IVC rendezvous separately with the spacecraft in this orbit; an S-IVC burn is generally required to reach this orbit since the launch vehicle itself cannot in general inject a fully-loaded S-IVC into that high an orbit. The mission sequence for each launch is as follows [parentheses indicate S-IVB rather than S-II if a three-stage rather than two-stage launch vehicle is used]:

1. Launch.

2. Shutdown of S-II (S-IVB) in 100 nautical mile circular orbit.

3. Coast (or run J-2S on idle mode) in the circular orbit for less than one revolution--coast time is determined by inertial direction of line of apsides of the elliptical rendezvous orbit, which is in turn determined by the direction and magnitude of the hyperbolic excess velocity vector for the specified mission.

4. Restart S-II (S-IVB), burning to depletion and separate S-IVC. In the case of S-II idle mode operation, only one or perhaps two J-2S's would be kept running and then brought up to full thrust for this phase. The S-IVC is now on an intermediate elliptical orbit, typically of 2-1/2 hours or less orbit period and apogee altitude between about 1,000 - 3,000 nautical miles.

5. First S-IVC burn for self-transfer of the S-IVC to the rendezvous orbit.

The sequence for the spacecraft launch is the same except that it is of course injected directly into the rendezvous orbit by the S-II (S-IVB) second burn. For a 180,000 lb. spacecraft, e.g., this rendezvous orbit would have a period of between about 4-6 hours and apogee altitude of 6,000 - 12,000 nautical miles, depending on whether the launch vehicle is two or three stages.

The S-II does not, of course, presently have restart capability. With conversion to J-2S (either uprated or non-uprated) however, this would not appear to be a major stage modification.

6. After rendezvous, the S-IVC's are docked in series to the spacecraft.

7. Each S-IVC is then restarted, burned to depletion, and jettisoned before ignition of the next one, completing the planetary injection maneuver.

Results

Payload-velocity curves for two and three-launch elliptical orbit rendezvous missions are shown in Figure 2, for cases where either two-stage or three-stage uprated Saturn V's are used for each launch. For cases of mixed two and three-stage launch vehicles, such as if the S-IVC's were launched with two-stages and the spacecraft with a three-stage, the results would be intermediate. The ideal ΔV requirements including launch window allowance for the 1975 Venus lightside, 1975 Mars twilight, and 1977 triple-planet flyby missions are indicated on the velocity scale.

Gravity losses were accounted for in an approximate manner based on previously generated curves for gravity loss ΔV vs. ideal ΔV and initial thrust-to-weight ratio for escape from a circular orbit. The following assumptions were made in this accounting:

1. Thrust of the J-2S used in the S-IVC is 235,000 lbs. Better performance might be attained operating at higher thrust and lower Isp.

2. Gravity losses during the S-IVC first burn (self-transfer to the rendezvous orbit) are negligible since initial thrust/weight in this phase is approximately .85.

3. Total gravity losses during the earth escape injection from the rendezvous orbit with multiple S-IVC's in series are the same as a single-stage injection from a 100 nautical mile circular orbit for the same ideal ΔV and T/W_o. This actually over-estimates the losses since (a) it is known that, for a given ΔV, the gravity losses decrease with increasing orbit eccentricity if the position relative to periapse at which the burn is started is optimized, and (b) the step-change in weight resulting from jettisoning S-IVC's will slightly decrease losses.

The results indicate that all of the manned flyby missions in the baseline JAG program can quite likely be accomplished with no more than three launches, using this version of Saturn V uprating plus elliptic orbit rendezvous; the Venus flyby missions (single-planet) can be accomplished with only two launches. The payload is approximately 175,000 - 210,000 lbs. for the 1977 triple-planet mission with three launches and 165,000 - 200,000 lbs. for the Venus mission with two launches, depending on whether the launch vehicles have two or three stages. These results are based on what are believed to be conservative estimates of launch vehicle and S-IVC performance. It should be noted, however, that the three-stage Saturn V is presently stack-limited to about 110,000 lbs. payload weight, and it remains to be determined what launch vehicle modifications would be required to carry much heavier payloads, e.g., an S-IVC, on top of the S-IVB.

Comparative results using a 263.5 nautical mile circular parking orbit are shown in Figure 3. It is important to first note that since the S-IVC weighs only about 287,000 lbs. fully loaded including IU and aft interstage, there would be no point in uprating the Saturn V beyond this point without increasing the S-IVC propellant capacity if restricted to circular orbit rendezvous.

This is illustrated in Figure 3, where circular orbit rendezvous results are shown comparing the use of "standard" S-IVC and a stretched S-IVC with an additional 51,700 lbs. of propellant capacity. Additional stage inert weight was assumed to be 3.5% of the added propellant weight. With three launches, e.g., only about 145,000 lbs. could be injected on the Mars twilight flyby mission using standard S-IVC's; this is of course the same whether the launch vehicle has 340,000 lbs. payload capacity to low circular orbit or only 287,000 lbs. ("standard" S-IVC gross weight). With the S-IVC stretched so that its gross weight equals the payload capability of the uprated Saturn V, however, the Mars flyby spacecraft weight with three launches increases to 185,000 lbs.

Comparing the results of elliptic orbit rendezvous (Figure 2) and circular (Figure 3), some specific conclusions can be drawn. For three-launch missions of this uprated Saturn V, elliptic orbit rendezvous with two-stage launch vehicles and standard S-IVC's provides slightly better performance than circular orbit rendezvous with stretched S-IVC's (about 320,000 lbs. gross weight). Compared only on the basis of the standard S-IVC, elliptic orbit rendezvous yields approximately a 40,000 lbs. increase in payload for a given mission ΔV. This latter figure increases to about 75,000 lbs. if three-stage Saturn V's are used for the elliptic orbit rendezvous missions.

Alternately, the use of elliptic orbit rendezvous with three-stage launch vehicles could result in one less launch being required; it is seen by comparing Figures 2 and 3 that, e.g., three three-stage launches with elliptic orbit rendezvous gives slightly better performance than four launches to circular orbit using standard S-IVC's (with stretched S-IVC's this does not hold).

Standard Saturn V's (Non-Uprated) - DAC Calculations

Since the non-uprated two-stage Saturn V (SA-516) can place only about 265,000 lbs. in a 100 x 263.5 nautical mile orbit, the "standard" circular orbit rendezvous mode therefore requires the S-IVC to be off-loaded by about 20,000 lbs. Performance can be improved if the S-IVC instead carries a full load of propellant and is started suborbitally, for either circular or elliptic orbit rendezvous. In the former case, the S-IVC injects itself into the 100 x 263.5 nautical mile orbit and then circularizes at 263.5 nautical miles; in the latter case the S-IVC shuts down and coasts in a 100 nautical mile circular orbit and then restarts for self-transfer into the elliptical rendezvous orbit.

Calculations have been carried out for these cases at the Douglas Aircraft Space Systems Center; their results are shown in Figure 4 (with their data converted from V_∞ in emos to ΔV above circular orbit). The spacecraft was assumed to be launched by a three-stage Saturn V, the S-IVC's by two-stage Saturns. These data include allowances for 4% gravity losses and 3% performance reserves in the ΔV's. Also shown for comparison are curves for circular orbit rendezvous with orbital start of off-loaded S-IVC's.*

The comparison of elliptic and circular orbit rendezvous indicates an increase of about 40,000 lbs. payload for the same number of launches. Also significant is the figure of about 200,000 lbs. payload for four launches on the 1977 triple-planet flyby with elliptic orbit rendezvous and suborbital S-IVC start. This indicates that any of the JAG baseline missions can be carried out with four non-uprated** Saturn V's using this mode.

Conclusions

1. Elliptic orbit rendezvous provides substantial performance improvements over circular orbit rendezvous by allowing utilization of the full performance capability of the launch vehicles.

2. Using elliptic orbit rendezvous, it should be possible to carry out all the Mars flyby and multi-planet flyby missions in the baseline JAG program with four launches of standard Saturn V's or three launches of the uprated Saturn V considered in this memo (stretched S-IC, uprated F-1 and J-2S). Venus flybys can be accomplished with two uprated Saturn V's.

3. There is no point in uprating the Saturn V beyond about 287,000 lbs. (gross weight of an S-IVC including IU and aft interstage) to low orbit for the flyby missions unless (a) the elliptic orbit rendezvous mode is utilized or (b) the S-IVC is "stretched" to accommodate a greater propellant load, or (c) the spacecraft weighs more than 287,000 lbs.

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*Hand calculations by the author do not bear out the difference in slope of the payload-velocity curves shown in Figure 4 comparing suborbital vs. orbital start for circular orbit rendezvous. Rather, a difference of about 400 fps in ΔV is indicated over the entire range of payload weight. However, this discrepancy does not affect the conclusions of this memorandum.

**Except for modifications required to allow the higher payload on top of an S-IVB.

4. With uprated Saturn V's, approximately the same performance is attained with standard S-IVC's using elliptic orbit rendezvous as with stretched S-IVC's ($\Delta W_p \simeq 50{,}000$ lbs.) using circular orbit rendezvous.

5. If uprated Saturn's are to be used for elliptic orbit rendezvous, one or both of the following additional modifications will be required in order to use this mode to best advantage: (a) restart or idle mode (one or two engines) capability for the S-II stage if using two-stage Saturn V's, (b) increasing the stack limit on the S-IVB to at least the gross weight of the spacecraft if three stage Saturn's are to be used. This latter improvement is desirable even for non-uprated Saturn's so that the spacecraft could be launched by a three-stage Saturn V.

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Attachments
Figures 1-4

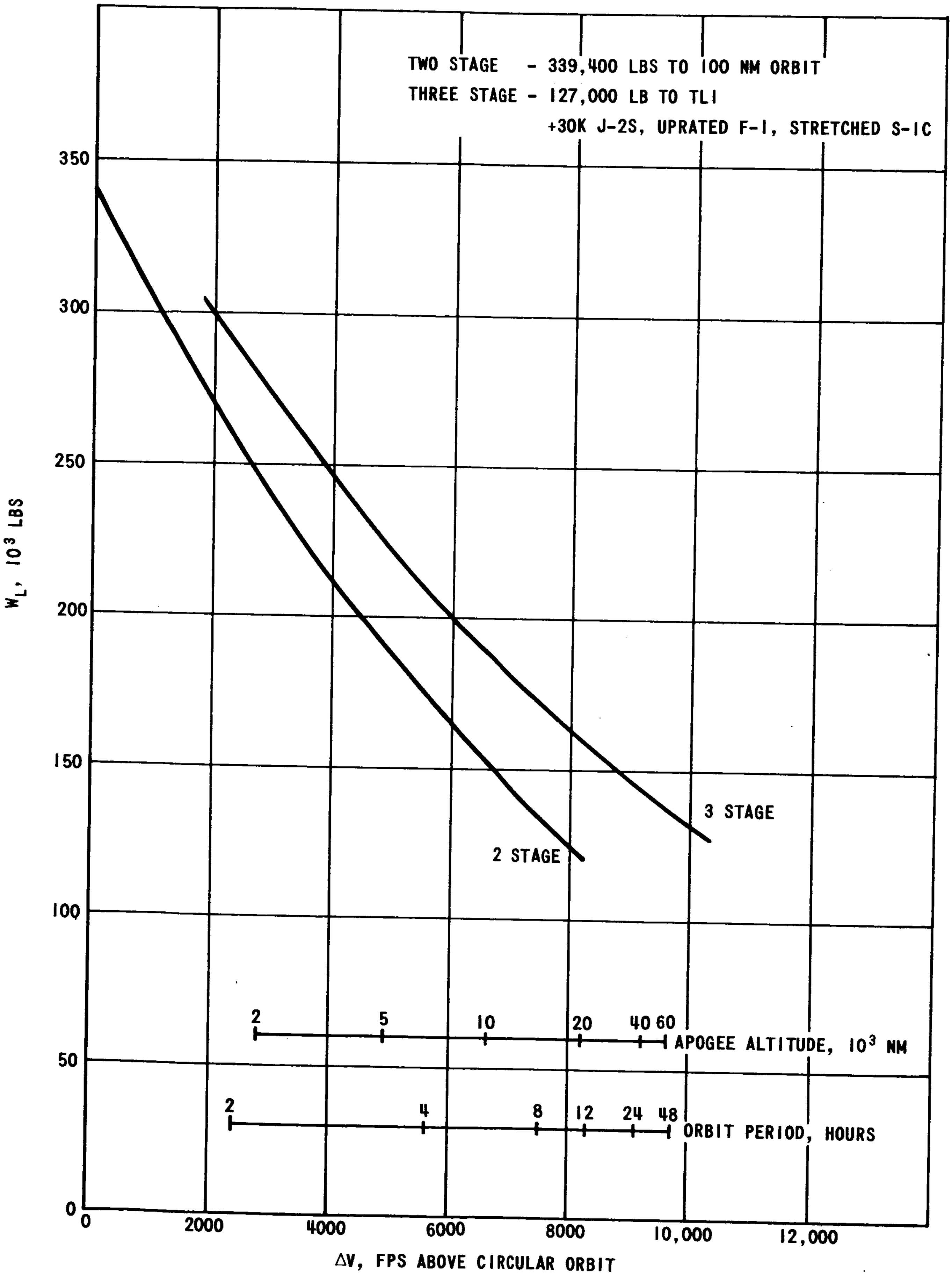

FIGURE 1 - PAYLOAD VS VELOCITY, UPRATED SATURN V

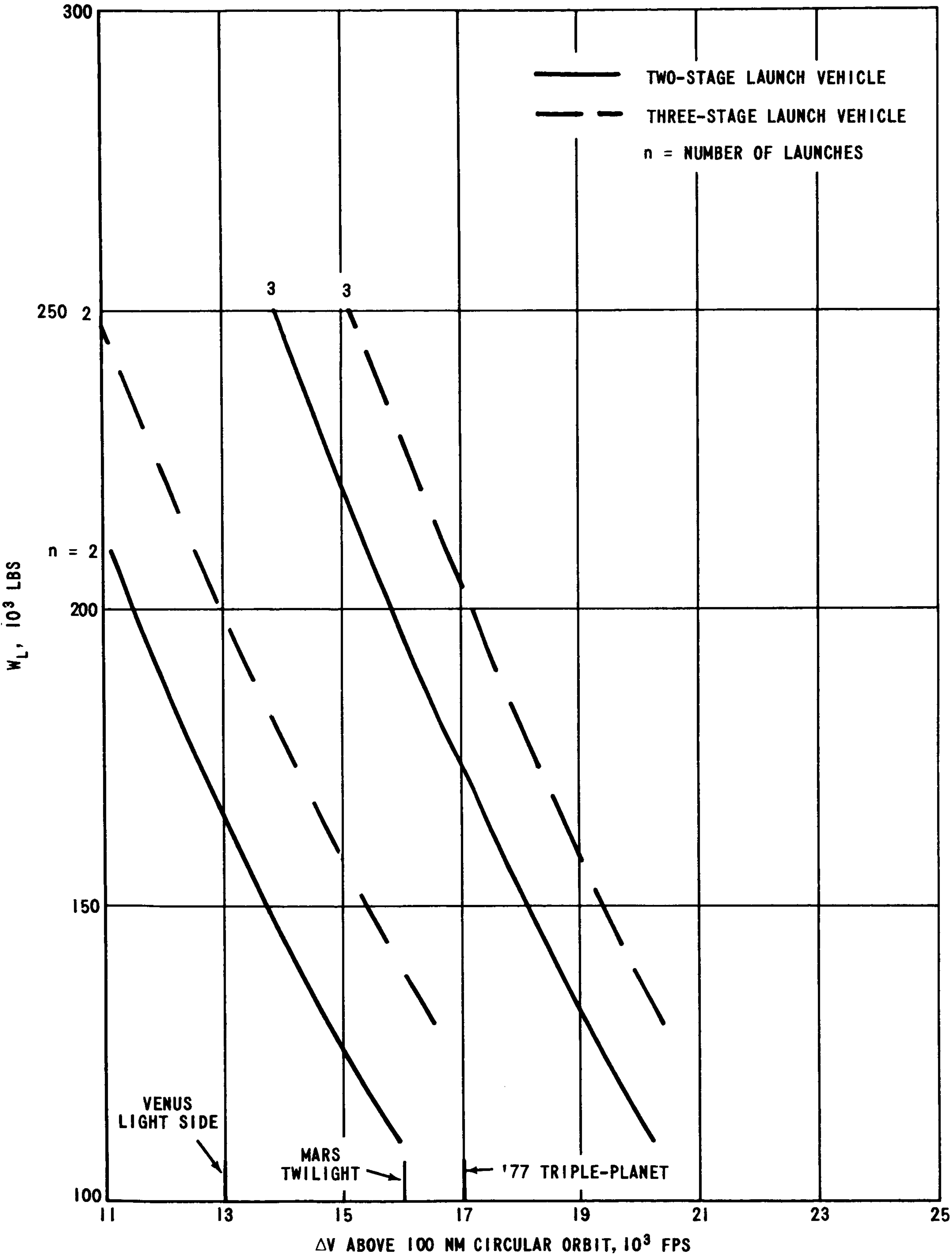

FIGURE 2 - PAYLOAD VS VELOCITY FOR MANNED FLYBY MISSION, ELLIPTIC ORBIT RENDEZVOUS, "STANDARD" S-IVC

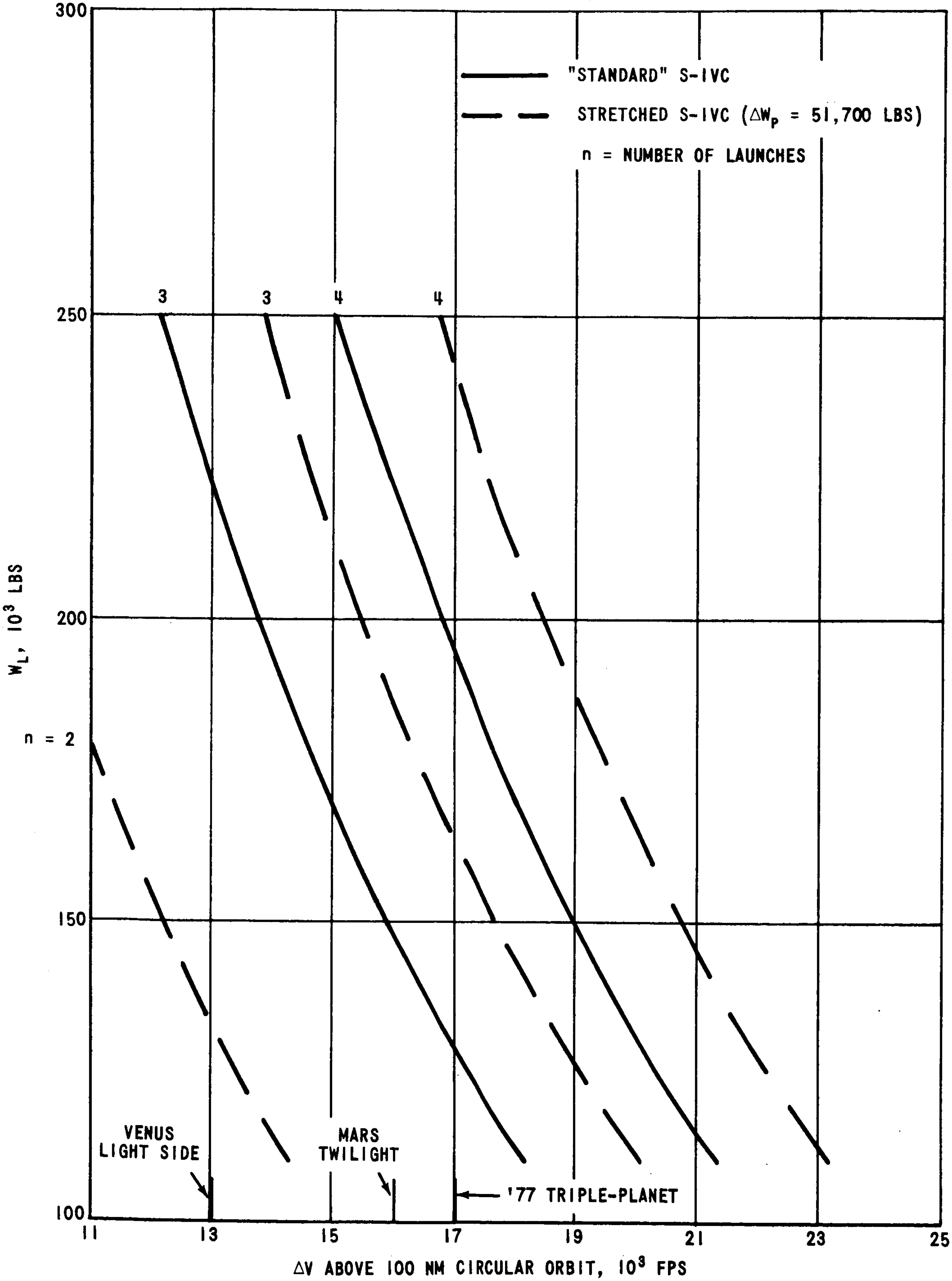

FIGURE 3 - PAYLOAD VS VELOCITY FOR MANNED FLYBY MISSION, CIRCULAR ORBIT RENDEZVOUS, UPRATED SATURN V'S

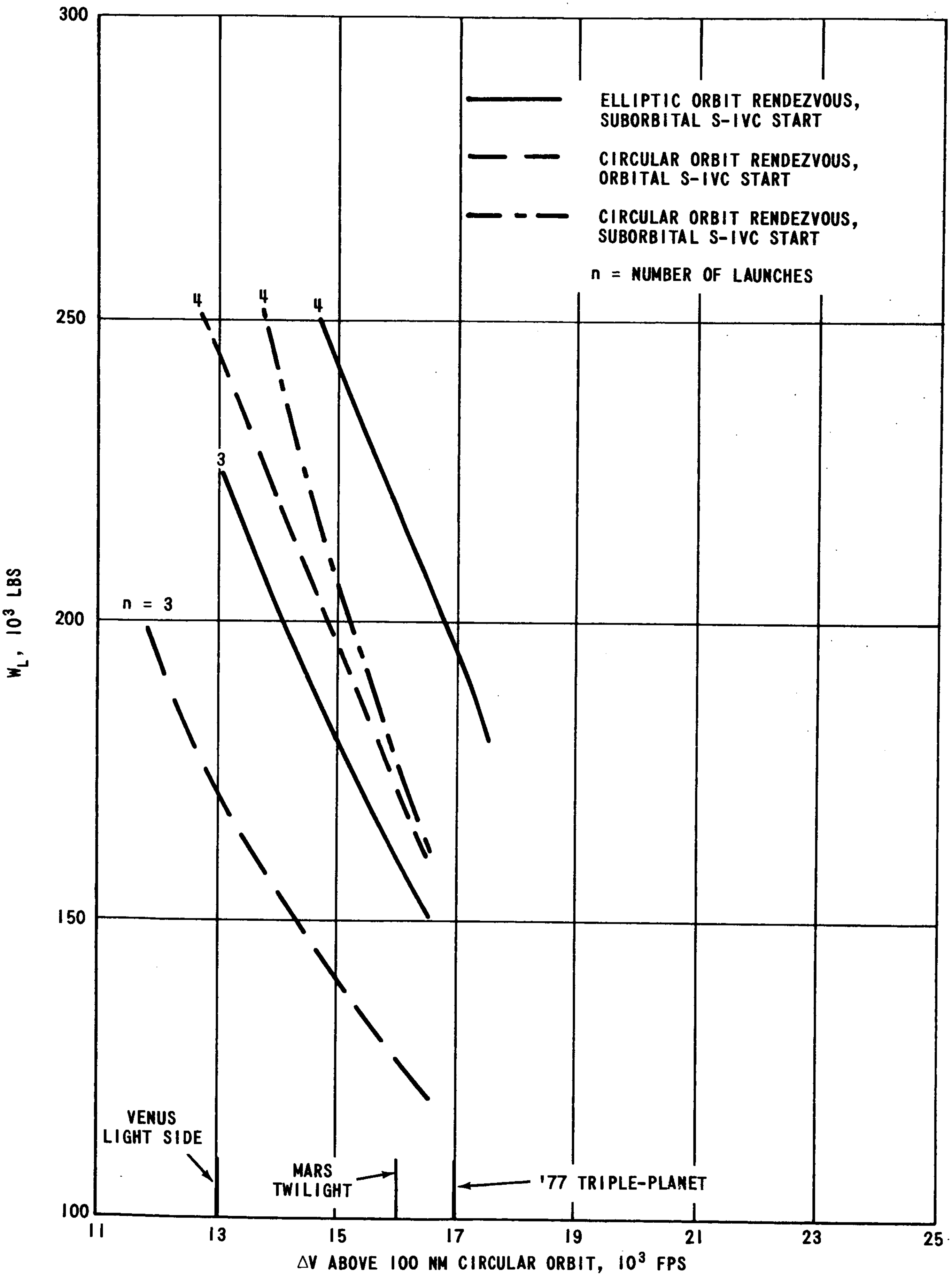

FIGURE 4 - PAYLOAD VS VELOCITY, STANDARD SATURN V'S

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